User's Guide for Biome-BGC MuSo v2.2

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INTRODUCTION

Biome-BGC is a widely used, popular biogeochemical model that simulates the storage and flux of water, carbon, and nitrogen between the ecosystem and the atmosphere, and within the components of the terrestrial ecosystems (Thornton, 2000). Biome-BGC was developed by the Numerical Terradynamic Simulation Group (NTSG), University of Montana (http://www.ntsg.umt.edu/project/biome-bgc). Note that the the currently available model version is 4.2.

Seveal researchers used and modified the original Biome-BGC model in the past. Most recently our research group developed Biome-BGC to improve the ability of the model to simulate carbon and water cycle in managed herbaceous ecosystems (see Hidy et al., 2012). The modifications included structural improvements of the model (e.g., the simple, outdated, one-layer soil module was replaced by a multilayer soil module; drought related plant senescence was implemented; model phenology was improved) and also management modules were developed (e.g. to simulate mowing, grazing). Although the modifications aimed to support the use of Biome-BGC in herbaceous ecosystems, the modified model can also be used in forest related studies, where the multilayer soil module can be used to perform more realistic simulations in terms of soil hydrology.

Since the publication of the Hidy et al. (2012) study additional modules were developed to simulate cropland management (e.g., planting, harvest, ploughing, application of fertilizers). Forest thinning was also implemented and included as a possible human intervention, and dynamic (annually varying) whole plant mortality was implemented in the model to enable more realistic simulation of forest stand development. Annually varying management options were also introduced. In the most recent model version separate pools have been defined for fruit following the method of Ma et al. (2011) to support cropland related simulations. Detailed description of the modificaitons are given in Appendix A.

This User's Guide was created to provide practical information for the use of the improved model. The Hidy et al. (2012) study used Biome-BGC v4.1.1 with previous modifications made by Max Planck Institute, Germany (we refer this version as Biome-BGC 4.1.1 MPI version; see Trusilova et al., 2009) as the starting point for model developments. Our improved model is called **Biome-BGC MuSo v2.2** (where the abbreviation refers to **Mu**ltilayer **So**il Module). Biome-BGC MuSo 2.2 is the updated version of MuSo v1.0, v1.1 v1.2, v1.3, v2.0 and v2.1 (v2.2 include developments and bugfixes, plus additional control is implemented to avoid impossible values set in the INI files and within the meteorology input data). Note that NTSG continues to develop the original model with the inclusion of management with a new disturbance handler module. In their implementation disturbance (or management) is described by a separate disturbance descriptor file. Our implementation of disturbance is different from the NTSG approach, as we included management settings in the

INI file of the model (note that in MuSo v2.2 there is an option to use additional management rules provided in separate text files).
Prior to reading this document further the reader should get familiar with the documentation of the original model (Biome-BGC v4.1.1; see Thornton, 2000 and Trusilova et al., 2009). The present document provides detailed decription about the differences between Biome-BGC v4.1.1 MPI version and the Hidy et al. (2012) developments, and the new modifications (including forest thinning with optional clearcut simulation, annually varying whole plant mortality, cropland management, and annually varying management options, and optional groundwater depth control for lowland ecosystems). We suggest to get a copy of the Hidy et al. (2012) paper as well, in order to see simulation results and calibrated parameters based on eddy covariance measurements performed in Hungary. Please contact Zoltán BARCZA (bzoli@elte.hu) for a reprint of the Hidy et al. (2012) paper if you do not have access to that publication.

STRUCTURE OF THE MODIFIED INITIALIZATION FILE

Due to the modifications of the model structure and the implementation of the new management modules, extension of the INI file was necessary. Below we introduce the changes made in the INI file of the model. An example INI file is given in Appendix B.

Modified initializing blocks

SITE block:
There are some modifications within the SITE block. New lines are also used here.

- instead of effective soil depth **maximum depth of rooting zone** is used (m)
- **mean annual air temperature** (Celsius) has to be defined (long term mean temperature, e.g. 1961-1990 mean, or 1981-2010 mean). It is used by *multilayer_tsoil.c* to calculate temperature of the different soil layers
- **runoff parameter** (mm) – used by *multilayer_hydrolprocess.c* (default is 0.1; see Campbell and Diaz (1988) for alternative parameterization of runoff parameter)
- **soil moisture content at wilting point, field capacity and saturation** at the simulation site (m^3 m^{-3}). It is used by *multilayer_hydrolprocess.c* (if no data are available, it should be set to 999.9, so the model will estimate them based on empirical functions)

OUTPUT_CONTROL block:
After the first line a new line was inserted into the OUTPUT_CONTROL block. The second line now defines a filename where internal model parameters will be written:

- **filename** for the Biome-BGC internal variables (control)

The rest of the block is unchanged.

Note that due to modification of the model logic we defined new internal variables, some of which can be written to the output binary files. Within Biome-BGC source code the index of variables that can be written out are defined in output_map_init.c. The modified and the new output variables are described in Appendix D. In MuSo v2.2 the annual text file was modified: the annual net changes of the ecosystem's carbon and nitrogen balance caused by management and senescence are also written out.

New initialization blocks:

The following blocks were defined to control growing season estimation and to describe different management activities on the simulated ecosystem. Each management type can be activated or deactivated for a given simulation independent of the other management types. Implemented management types are documented in Appendix A.
Growing season definition block is located after the N_STATE block. The management block starts with the following lines after the annual output block:

```
-------------------
MANAGEMENT_SECTION
-------------------
```

The growing season block and the management blocks must be present even if the user deactivates them (i.e. the structure of the INI file is fixed, similarly to previous versions of Biome-BGC).
A management type can be activated if the flag in the first line of the block is set to 1, or if there is a filename present in the first line of the block that refers to external management descriptor (see below). If the flag is 0 it means that the management type is deactivated.
For each management type maximum 7 events can be defined for each year. In case of less than 7 events 999.9 can be used to skip some of the events.

The new blocks are as follows:

- *GROWING_SEASON block* – meaning of the parameters is described in Appendix A, Section 1.1 (see also Appendix B for example INI file)
  If the user wants to use the new growing season estimation method the first line of the block must start with 1 (flag to use GSI index to calculate growing season). If USER-SPECIFIED PHENOLOGY is set to zero in the EPC file then the GSI method will **not** be used even if the GSI flag is set to 1.
- *PLANTING block* – parameters are described in Appendix A, Section 2.6
- *THINNING block* – parameters are described in Appendix A, Section 2.5
- *MOWING block* – parameters are described in Appendix A, Section 2.1
- *GRAZING block* – parameters are described in Appendix A, Section 2.2
- *HARVESTING block* – parameters are described in Appendix A, Section 2.3
- *PLOUGHING block* – parameters are described in Appendix A, Section 2.4
- *FERTILIZING block* – parameters are described in Appendix A, Section 2.5

To illustrate the structure of the management blocks here we present an example for the MOWING block. The structure of the other blocks is very similar.

```
MOWING
0                   (flag) do MOWING? 0=no; 1=yes; filepath=reading from file
0                   (flag) mowing method? 0 - on fixday, 1 - if LAI greater than a fixed value
6.0                 (int) fixed value of the LAI before MOWING (fixvalue method)
1.0                              (int) fixed value of the LAI after MOWING (fixvalue method)
150 234 999.9 999.9 999.9 999.9 999.9    (yday) MOWING day
1.0 1.0 1.0 1.0 1.0 1.0 1.0      (int) value of the LAI after MOWING (fixday method)
0   0   0   0   0   0   0        (%) transported part of plant material
```

See Appendix B for a complete example for the new INI file structure.

OPTION TO USE ANCILLARY MANAGEMENT FILES TO SIMULATE ANNUALLY VARYING HUMAN INTERVENTION

Biome-BGC MuSo v2.2 has a built-in option to define annually varying management settings for all implemented management types. This can be achieved by creating ancillary text files with a given structure.
The names of the ancillary management files can be set by the user, but for clarity we suggest to use names that are identical with the name of the management block defined within the INI file (e.g. mowing.txt, fertilizing.txt, grazing.txt, harvesting.txt, planting.txt, ploughing.txt, thinning.txt). The text files are only utilized if the first line of the given management block in the INI file contains reference to the file (e.g. in case of mowing the MOWING section should look like this:

```
MOWING
management/mowing.txt       (flag) do MOWING? 0=no; 1=yes; filepath=file
0                           (flag) mowing method? 0 - on fixday, 1 - fixLAI
```

In this example the mowing.txt file is supposed to be in the `management` directory relative to the directory of the model executable.
The ancillary management files only contain rows that define the 7 events for the specific management type. In case of mowing the mowing method and the LAI before mowing is always defined in the INI file, while the other settings (mowing days, LAI after mowing, transported part) are given in the ancillary file (if defined). Similarly to the 7 management setting within the INI file 999.9 means that the given management event should not be considered (applicable if there are less then 7 management events per year; note that there can be years when there is no management at all).
Note that in case of defined ancillary file the 7-event-lines given in the INI file are not considered. In the present example the ancillary mowing.txt should contain these lines:

```
MOWING day (only fixday method)
150 234 999.9 999.9 999.9 999.9 999.9
170 244 999.9 999.9 999.9 999.9 999.9
180 999.9 999.9 999.9 999.9 999.9 999.9
value of the LAI after MOWING
1.0 1.0 1.0 1.0 1.0 1.0 1.0
2.0 1.5 1.0 1.0 1.0 1.0 1.0
2.0 1.8 1.0 1.0 1.0 1.0 1.0
transported part of plant material
0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0
```

In this example normal simulation is performed for 3 years, so in each block 3 lines are repeated. The first line in MOWING day block belongs to the first simulation year, then the second is to the second year, and finally the third is to the third simulation year. Number of lines must be equal with number of simulation years defined within the INI file.
Additional examples are given in Appendix E separately for each managemet type.

MODIFICATIONS MADE IN THE ECOPHYSIOLOGICAL FILE

The modifications of the model logic led to changes in the ecophysiological parameterizatiton as well. An example EPC file is given in Appendix C.

New ecophysiological parameters

- **line 8 (parameter 6)**: yearday to start fruit allocation (YFL). Default value is 150.
- **line 16 (parameter 14)**: the ratio of fruit and leaf carbon content (allocation parameter, new fruit C: new leaf C; FC:LC). Default value is 0.5.
- **line 24 (parameter 22)**: the carbon and nitrogen ratio of fruit (C:N ratio of fruit; CN_fr). Default value is equal to the carbon and nitrogen ratio of leaf.
- **line 33-35 (parameter 31-33)**: the fruit litter/labile/cellulose/lignin proportion (FLaP, FCeP, FLiP). Default values are equal to litter/labile/cellulose/lignin proportions of leaf litter.
- **line 44 (parameter 42)**: fraction of leaf nitrogen in PeP Carboxylase for new C4 photosysthesis routine (FLNP). Default value is 0.03.
- **line 48 (parameter 46)**: soil water content ratio: start of conductance reduction (WCRS). If no available data: set it to 999.9 (no water stress above field capacity where the latter is estimated from soil texture using epririca relationship).
- **line 49 (parameter 47)**: soil water content ratio: complete stomatal closure (WCRC) (note that in the original model leaf water potential: complete conductance reduction (WCRE) was used as limiting factor, also for parameter 46). If no available data: set it to 999.9 (below wilting point complete stomatal closure).
- **line 54-55 (parameter 52-53)**: senescence (drought stress related) mortality coefficient (effect) on aboveground/belowground plant material (SMCA/SMCB). These parameters might be important to simulate the carry-over effect of drought stress during the consecutive year. Default values are 0.01.
- **line 56 (parameter 54)**: turnover rate of wilted standing biomass (senescenced leaves) to litter (TRWB). Default value is 0.01.
- **line 57 (parameter 55)**: turnover rate of cut-down (but not transported, i.e. left at the site) non-woody biomass to litter (TRCN). Default value is 0.05. This parameter controls harvested plant residues in croplands or clipped grass leaves in case of mown grasslands. In case of forests this parameter controls the fate of (previously living) leaves on cut down trees (if thinning option is switched on), but it also controls the turnover of dead coarse root (stump) into coarse woody debris (cwd). Implementation of this turnover process was needed to avoid C and N balance errors caused by large fluxes between specific pools.
- **line 58 (parameter 56)**: growth respiration cost per unit of carbon growth (GRC). Default value is 0.3. In the original model this parameter was constant fixed within the source code.
- **line 59 (parameter 57)**: daily N denitrification proportion (NDP; amount of N mineralization that is available to volatilization each day). Default value is 0.01. In the original model this parameter was constant fixed within the source code.
- **line 60 (parameter 58)**: N mobile proportion (NMP; this is the proportion of mineralized N that is leached each day if there is deep percolation). Default value is 0.1. In the original model this parameter was constant fixed within the source code.
- **line 61 (parameter 59)**: Maturity coefficient for calculating maximum rooting depth (MC). This parameter defines the time within the growing season when maximum

rooting depth (set by the INI file) is reached. Default value is 0.5 which means the middle of the growing season.

Modified ecophysiological parameters

- **lines 50-51 (parameters 48-49)**: soil water potential: start of/complete conductance reduction (SWPS, SWPC). Note that in the original model leaf water potential: start of/complete conductance reduction (LWPS, LWPC) were used here. If soil water potential is given by the user while parameters 46 and 47 (soil water content ratio) are undefined, then soil water potential controls stomatal closure. If parameters 46-49 are all undefined (999.9) then the model calculates stomatal closure based on internally estimated field capacity and wilting point. If parameters 46-49 are all defined then soil water content ratio (parameters 46 and 47) are used, parameters 48 and 49 are ignored.

Note that in the original model there were only 43 EPC parameters (MuSo v2.2 has EPC 60 parameters), which means that the number of parameters increased. We are fully aware that high number of adjustable parameters might complicate calibration and application of the model. However, our intention was to extend the EPC file with some of the parameters that were „burned in" within the source code but might need adjustment. Implementation of the new multilayer soil module and fruit yield also involved the definition of new EPC parameters. In the simplest case these parameters should be left intact by the user. In any case, sensitivity analysis is needed to check whether the new parameters has strong influence on the variability of the output. We are implementing a so-called workflow within the frame of the BioVeL project to enable simple sensitivity analysis of Biome-BGC MuSo. Please contact us for access to the workflow environment.

LIST OF MODIFICATIONS IN THE SOURCE CODE (C FUNCTIONS)

Below we describe the changes in subroutines of the source code.

1. Modified subroutines

- *annual_rates.c*: completing leaf and fineroot litterfall rates with fruit litterfall rates.

- *canopy_et.c*: calculates only the canopy evaporation and transpiration based on Penman-Montieth method. The necessary conductance values are calculated separately in a new subroutine: *conduct_calc.c* (see below)

- *check_balance.c*: new variables are defined and further control is implemented to avoid negative stocks.

- *daily_allocation.c* and *spinup_daily_allocation.c:*
  - new flag for nitrogen limitation type
  - nitrogen limitation calculation is based on the averaged mineralized N content of the root zone
  - warning for negative GPP

  - completing leaf and fine root allocation rates with fruit allocation.

- *daymet.c*:
  - initializing soil temperature values in multilayer soil
  - on the first day original soil temperature calculation method is used
  - correction for handling the daylight average temperature correctly (now daylight average temperature is read from the meteorology file so it is not calculated within the source code; see below)

- *dayphen.c*: initiation and cessation of growing season ('onday' and 'offday') are stored in phenology structure in order to use in the new subroutines (GSI calculation)

- *decomposition.c*: calculates the rate constant scalar in multilayer soil using root zone averaged values (soil temperature, soil metric potential). In case of water stress days (soil moisture content is below a critical level) the water limitation factor is calculated based on relative water content instead of soil water potential.

- *epc_init.c*: modifications to handle the new EPC parameters (see above)

- *maint_resp.c:*
  - calculates layer-specific soil temperature exponents (regarding to maintenance respiration of root in the different soil layer)
  - completing leaf and fine root respiration fluxes with fruit respiration flux.

- *metarr_init.c*: modifications for handling the daylight average temperature correctly

- *mortality.c*:
  - dynamically changing whole plant mortality parameter (WPM) can be set by the user by creating mortality.txt file in the model folder/directory (next to model executable)
  - completing with fruit mortality fluxes.

- *photosythesis.c*: correction of C4 photosynthesis routine based on the work of Di Vittorio et al. (2010) (using source code of Biome-BGC 4.3 beta).

- *precision_control.c*: checking precision of gresp_transfer (not implemented in earlier model version) and check of new variables.

- *prephenology.c*: onday and offday are stored in phenology struct in order to use in the new subroutines (GSI calculation).

- *sitec_init.c:*
  - instead of soil depth, maximum rooting depth parameter is used (positive number)
  - soil layer depths (positive numbers) are fixed: 0-10, 10-30, 30-100, 100-200, 200-300, 300-500 cm; soil layer thickness is calculated
  - new init parameters: runoff parameter; measured volumetric water content at wilting point, field capacity, saturation (if it is available)
  - calculation of the saturation, field capacity, wilting point value of hydrological parameters

- *summary.c*:
  - new summary output variables are calculated - VEGC, LITRC, SOILC, TOTALC, SR (soil respiration), NBP;
  - NEE is positive if ecosystem is net C source
  - carbon content change from management and disturbance is summarized

- *bgc_constant.h; bgc_epclist.h; bgc_struct.h; firstday.c; make_zero_flux_struct.; output_init.c; pointbgc_struct,c; presim_state_init.c; restart_io.h; state_init.c; summary.c*; *state_update.c; zero_srcsnk.c*: new pools and fluxes (for multilayer soil modules, fruit simulation, GSI calculations, management modules), calculation of summarized soil stocks

- *bgc*.c; *pointbgc.c*; *bgc_func.h; bgc_io.h; pointbgc.c; pointbgc_func.h; spinup_bgc.c*: modifications due to new subroutines and new variables.

- *output_map_init.c*: modifications due to new variables (see Appendix D)

2. New subroutines

GSI calculation

- *GSI_calculation.c*:
  - calculation of pheonological state of vegetation (onset and offset day) from Tmin, VPD, daylength and cumulative Tavg based on literure.
  - snow cover estimation based on precipitation, average temperature and shortwave radiation – growing season does not start until there is snow cover (this is a new feature since Biome-BGC MuSo v2.1)

- auxiliary function: *GSI_init.c*

- futher modifications in: *dayphen.c* and *prephenology.c*

Multilayer soil modules

- *multilayer_tsoil.c*:
  - surface soil temperature change caused by air temperature change
  - shading effect of vegetation is calculated based on an exponential function of LAI (if soil temperature is lower than air temperature the effect is zero)
  - deeper soil layer temperature calculations are based on temperature gradient between surface and that below 3m

- *multilayer_hydrolparams.c*:
  - calculation of soil moisture content, soil water potential, hydraulic conductivity and hydraulic diffusivity as a function of volumetric soil water content and constants related to texture
  - boundary layer (below 3 m) is special; it has „infinite depth", constant temperature (equal to the annual air average temperature of the site) and soil moisture content (field capacity)
  - average values are estimated regarding to the root zone

- *multilayer_hydrolprocess.c*:

  - calculation of the change of soil water content layer by layer taking into account soil hydrological processes (precipitation, evaporation, runoff, percolation, diffusion) using dynamically changing time step (the latter is defined based on the amount of precipitation)
  - bottom layer (200-300 cm) is special: the percolated water is net loss for the system, while the diffused water is net loss or net surplus for the system depending on the direction of the diffusion
  - note that in Biome-BGC MuSo v2.2 upward diffusion from the boundary (below 3 m) is possible (as the boundary layer has constant soil moisture we assume that the diffusion from or into the boundary layer is occured a 100m depth layer with a field capacity soil moisture content)
  - theoretical upper limit of water content: saturation value (amount above saturation is stored on the surface as a pond water)
  - theoretical lower limit of water content: hygroscopic water content (percolation, diffusion or evaporation fluxes can be limited due to dry soil).

- *multilayer_transpiration.c*:
  - calculating fractional transpiration fluxes from sum of the transpiration flux (determined in canopy_et.c) based on the soil water status of the soil layers
  - root water uptake is only possible from the layers where root is located
  - if stomata is not closed root water uptake is divided between soil layers when enough soil moisture is available
  - if stomata is closed only cuticular water exchange is possible
  - theoretical lower limit of water content: hygroscopic water content (transpiration fluxes can be limited due to dry soil)

- *multilayer_rootdepth.c*:
  - calculation of changing rooting depth based on empirical function
  - the maximum rooting depth is on maturity day which is calculated using new EPC constant (maturity coefficient)
  - calculating the number of the soil layers in which root can be found and calculating the relative soil layer thickness
  - calculating the soil mineral N content of rooting zone taking into account changing rooting depth

- *multilayer_sminn.c*:
  - calculating the change of content of soil mineral nitrogen in multilayer soil
  - decomposition of soil organic matter (N mineralization) and plant N uptake are calculated separately in daily_allocation routine, but N loss/surplus (due soil and plant processes) are divided between root zone layers based on the N content of the layers
  - daily atmospheric N deposition is displayed in the first (top) soil layer but not in the entire root zone
  - biological N fixation is divided between root zone layers based on the quantity of root in the given layer (calculated in *multilayer_rootdepth.c*)
  - nitrogen leaching is calculated in the end of this subroutine in order to avoid negative pools based on the percolation fluxes and the soil mineral N content

- *groundwater.c*:
  - calculating the effect of elevated groundwater on soil hydrology. Groundwater can be controlled by creating a text file called groundwater.txt in the model

folder/directory (next to model executable) that contains daily data for the duration of the normal simulation.

- auxiliary function: *groundwater_init.c*

Senescence simulation

- *waterstress_days.c*: calculates the number of the days since water stress occurs during the vegetation period based on soil water status

- *conduct_limit_factors.c:* calculates the limitation factors for conductance calculation (user can set both volumetric soil water content (VWC) ratio or PSI data in EPC file, but in the calculations VWC ratio values are used)

- *conduct_calc.c:*
  - calculating the stress functions (multipliers for stomatal conductance calculation) for photosynthetically active photon flux density, vapor pressure, minimum temperature and soil properties in order to calculate conductance
  - soil related stress function is based on the averaged stress function for the root zone

- *senescence.c:*
  - abovegroung and belowground plant material senescence is occurring due to low soil water content during a prolonged drought period (number of days since water stres is calculated in *waterstress_days.c*)
  - mortality fluxes enter a temporary sensecence pool (standing dead biomass) from which dead plant material gradually enters the litter pool
  - turnover rates (of abovegrund/belowground dead plant material) can be set in EPC file (parameter 52-53)

Management modules

- *planting.c:* (auxiliary function: *planting_init.c*)

- *thinning.c:* (auxiliary function: *thinning_init.c*)

- *mowing.c:* (auxiliary function: *mowing_init.c*)

- *grazing.c:* (auxiliary function: *grazing_init.c*)

- *harvest.c*: (auxiliary function: *harvest_init.c*)

- *ploughing.c:* (auxiliary function: *ploughing_init.c*)

- *fertilizing.c:* (auxiliary function: *fertilizing_init.c*)

Removed (obsolete) subroutines

- *nleaching.c*: now included in *multilayer_sminn.c*

- *soilpsi.c*: now included in *multilayer_hydrolparams.c*

- *outflow.c*: now included in *multilayer_hydrolprocess.c* – percolation at the bottom soil layer

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APPENDIX A
DETAILED DESCRIPTION OF THE MODIFICATIONS

Below we provide theoretical basis for the model developments. Note that the majority of the changes is documented in Hidy et al. (2012) in detail, though there are some differences due to new developments and model refinements.

A1. Improvements of model structure

1.1 Improvement of model phenology

To determine the start of the growing season the phenological state simulated by the model can be used. We experienced that the start of the growing season internally calculated by the original model is unrealistically late, at least in case of herbaceous ecosystems in Hungary (Hidy et al., 2012). Biome-BGC has a built-in support for using a fixed date for start and end date of the growing season during the simulation. However, using fixed date large discrepancies are expected between the simulation results and measurement data because the start and end of the growing season exhibit large interannual variability. In order to avoid these problems (especially in relation with simulations under changing climate when prolongation of the growing season is expected) we have modified the phenology module of Biome-BGC.
We developed a special growing season index (*HSGSI*: *heatsum growing season index*), which is the extension of the GSI index introduced by Jolly et al. (2005). *HSGSI* (similarly to the original GSI) combines a set of variables into one variable for the estimation of the beginning and end of the growing season (heatsum, minimum air temperature, vapor pressure deficit and length of the day). HSGSI can be used optionally within the model (see settings in the INI file).
Parameters used to control phenology are the following:

- **snow cover** (critical amount of snowpack above which fully contstrained)
- **basic temperature** is needed to calculate heatsum
- **threshold limits** (under/above no/full constrained) of heatsum, tmin, vpd index and daylength index (8 parameters)
- **number of days to calculate moving average** from indices to avoid the effect of single extreme events
- ***HSGSI* limits** (start/end of growing season)
- **filename** of the estimated start and end of the vegetation periods (output file; it is created as control variable during simulation)

In the original model version snow cover does not affect nor the the start of the vegetation period, neither the photosynthesis. We implemented a new, dual snow cover limitation method in MuSo v2.1 and v2.2. First, growing season can only start if the snowpack is less than a critical amount (given in kg H_2O m^{-2} units; note that this is *not snow depth* but rather water content stored in the snowpack; it is up to the user to set the threshold if snow depth is known). Second, the same critical value also limits photosynthesis during the growing season (no carbon uptake is possible above the critical snow cover; we simply assume that no radiation reaches the surface if snow depth is above a pre-defined threshold). The snow cover estimation (also as the part of the *HSGSI* calculations that precedes the real simulations) is based on precipitation, mean temperature and incoming shortwave radiation (original model logic is used here). The critical amount of snow can be defined in the GROWING_SEASON

block of INI file. It is important to note that critical amount of snow is also used to limit photosynthesis in case of using original model phenology (which means that the flag to use HSGSI is 0 within the GROWING_SEASON block of the INI file). The default value of this critical snow cover is 5 kg/m^2 which is equivalent circa 5 cm fresh snow (but this is of course highly dependent on snow density, so the user should be cautious with this default value).

1.2 Improvement of the simulation of soil processes in Biome-BGC

Biome-BGC was primarily developed to simulate the carbon and water budget of forests (where soil moisture limitation is probably less important due to the larger rooting depth), therefore the soil sub-model was simple (one layer budget model). In order to improve the simulation of water fluxes a six-layer soil submodel was implemented into the model. Six layers provide an optimal compromise between the simulation accuracy and computational cost. In accordance with the soil layers we also defined new fluxes within the model.
The thicknesses of the active layers from the surface to the bottom are 0.1, 0.2, 0.7, 1 and 1 m (it means that the first layer is located at depth of 0-10 cm, the second is at 10-30 cm, the third is at 30-100 cm, the fourth is at 100-200 cm and the fifth is 200-300 cm). The thickness of bottom (6th, inactive) layer is 2 m, but the properties of this special layer do not change with time. It is assumed that its temperature is always equal to the annual average air temperature of the site, and its soil water content is equal to the field capacity (constant value). It is also assumed that the bottom layer can only be a sink of mineralized N (but can NOT be a source to the upper layers).
Soil texture is assumed to be constant with depth. The total active soil depth is 3 m with the root zone in the upper part of the soil (maximum possible rooting depth is 5 m, and its value can be set by a parameter in the INI file). Soil properties are calculated for each layer separately (see below).
Note that in the Hidy et al. (2012) publication only 4 soil layers were used; the 6 layer module is an improvement basically aimed to support forest related simulations where the deepest layer represents the water table that can be accessed by tree roots (if rooting zone is deep enough).
Water becomes available to the plant through water movement through the roots and root growth to take up water. To determine water uptake the correct simulation of both of these processes is necessary.
In case of herbaceous vegetation, fine root growth is simulated based on empirical method: in the growing season it increases from the first day (*ONDAY*) of the growing season until the maturity date (*MATUR_DAY*) based on a sigmoidal function (Campbell and Diaz, 1988). The actual rooting depth is calculated as the fraction of maximum rooting depth in terms of the fraction of time from onday to maturity. The maturity date can be set by the user using a new ecophysiological parameter (*matur_coeff)*. By default we may assume that it is the middle of the growing season (*matur_coeff*=0.5):

$$MATUR_DAY = ONDAY + matur_coeff \cdot (OFFDAY - ONDAY),$$

where *ONDAY* is the start, *OFFDAY* is the end of the growing season (days of the year).
The time-step of the rooting depth simulation is one day.
In case of forests, fine root growth is assumed to occur in the entire root zone represented by coarse roots (maximum depth of root zone is set by the INI file; see Appendix B. Note that in case of forest this depth does not change with time).
Since some of the soil properties depend on temperature, it is necessary to calculate soil temperature for each active layer; so the thermodynamics of the soil submodel is also

reconsidered in the developed model (see below). We assume that below the lowermost boundary (3 m to 5 m) the soil properties are constant: the soil temperature is assumed to be equal to the annual mean air temperature which can be set by a parameter; the other soil properties (soil moisture content, conductivity, and diffusivity) correspond to field capacity values (Chen and Dudhia, 2001).

1.2.1 Simulation of soil thermodynamics

In the developed model the daily soil surface temperature (average temperature of the top soil layer, with thickness of 10 cm) is determined based on the method of Zheng et al. (1993). It is assumed that the changes of daily soil surface temperature can be predicted from the changes of daily air temperature using empirical functions (a 10-day running average of daily air temperature is used as initialization value of the soil surface temperature). The relation between soil and air temperature also depends on the presence/absence of snowcover. The rate of the changes in soil temperature (the difference between soil surface temperature on actual and previous day) under snow cover is less (caused by low thermal diffusivity, and higher albedo). Therefore, different equations are used to simulate the rate of the changes in soil temperature if snowpack is present (Eq. 1 and Eq. 2 in Zheng et al. (1993), respectively). It is hypothesized that vegetation canopies can decrease soil temperature in growing season, because less radiation can be absorbed by the soil due to the shading effect of leaves. This shading effect is taken into account in the developed model based on the Beer-Lambert law using the simulated value of leaf area index (*LAI*) and one of the ecophysiological parameters of Biome-BGC, the light extinction coefficient (Eq. 3 in Zheng et al. (1993)).
The heat flux between soil layers can be estimated by the diffusion equation for soil temperature based on Fourier diffusion law. The simulation of the thermodynamic processes based on Fourier diffusion law would require finer grained calculations; therefore a nested 1-minute time-step based calculation would be necessary. It would mean high increase in model computational time. Instead, soil layer temperatures are estimated based on empirical formula with daily time step. The method is the following: the soil temperature below 3 meters can be approximated with the mean annual air temperature of the given site (lower boundary condition; set by the user in the INI file). The temperature of the surface layer (upper boundary condition) is estimated based on the method of Zheng et al. (1993): it is assumed that the change of the surface soil temperature is calculated by the change of the air temperature considering the insulating effect of the snowcover and the shading effect of the vegetation. The temperature of the intermediate soil layers is calculated assuming linear temperature gradient between top soil layer and 3 meter depth. The depth of a given soil layer is represented by the middle level of the given layer (e.g. the thicknesses of the top soil is 0.1 m, therefore its depth is represented at 0.05 m).

1.2.2 Simulation of soil hydrology

Among soil hydrological processes the original Biome-BGC only takes into consideration the *canopy interception*, *snowmelt*, *outflow* and *bare soil evaporation*. We have added the simulation of *runoff*, *diffusion* and *percolation* processes in order to improve the soil water balance simulation. Optional handling of seasonally changing *groundwater depth* (i.e. possible flooding) is also implemented beginning with MuSo v2.2 (e.g. flooding simulation for lowland forests).
Surface runoff is the water flow which occurs when the rate of rainfall on a surface exceeds the rate at which water can infiltrate into the soil.

Our runoff simulation method is semi-empirical and is based on the assumption that runoff increases as daily precipitation increases (Campbell and Diaz, 1988). Runoff is subtracted from precipitation and the remainder is available for infiltration. An empirical runoff parameter describes the surface storage condition and it defines the critical amount of precipitation over which runoff occurs using an empirical function

The downward movement of water within the soil is called *percolation*. The fraction flowing into the soil can be stored in root zone or lost by *deep percolation* (outflow at the bottom). In soil, a concentration gradient causes net movement of water molecules from high concentration regions to low concentration ones, and this gives the movement of water by *diffusion*.

The goal was to determine the average soil moisture content of each active soil layer and to calculate its diurnal changes. The surface layer is special, because this is the primary sink of precipitation and the source of bare soil evaporation. In the other layers only the processes of diffusion, percolation and root water uptake are occurring. At the bottom layer the hydraulic diffusivity is assumed to be zero, so that the soil water flux is due only to the gravitational deep percolation, which is a net water loss from the modeled soil layer. Root water uptake can occur from layers where roots are present. The transpiration flux of the ecosystem is assumed to be equal to the total root water uptake on a given day. The transpiration calculation is based on Penman-Monteith equation using stomatal conductance (original Biome-BGC logic is used). The transpiration fluxes are divided between layers accoring to the soil moisture limitation of the given layer (formula is presented below on Page 19; $coeff_{stoma}$) and to the root content (ratio of the actual soil layer depth and the total rooting zone).

Hydraulic conductivity and hydraulic diffusivity can change rapidly and significantly with changing soil moisture content. Though the main processes of Biome-BGC are based on daily time-steps, the simulation of the soil hydrological parameters required finer grained calculations; therefore a nested time-step based calculation was introduced into the soil hydrology sub-module. The time-step is dynamically changed (no precipitation event: 3 hours; small precipitation (<10 mm/day): 10 minutes; big precipitation (>10 mm/day): 1 minute.

The values of water content at wilting point (pF=4.2), field capacity (pF=2.5), and saturation are calculated using Clapp-Hornberger parameter which is estimated based on empirical function of soil composition (Clapp and Hornberger, 1978). In the developed model version these water content values can also be set by the user if measured data are available (in this case soil water potential is calculated based on these water content values instead of empirical functions).

The theoretical upper limit of the volumetric water content is the *saturation value*. In case of very large precipitation event if not all of the precipitation can infiltrate, *pond water* is generated on the surface. Water of the pond can infiltrate into soil after water content of top soil layer decreases below saturation level.

The theoretical lower limit of the volumetric water content is the *hygroscopic water*, i.e. the water content of air-dried soil. Negative soil water content (as well as negative carbon and nitrogen content) is not possible. Therefore, in case of large evaporation or transpiration (calculated based on the Penman-Montieth equation, and driven by meteorological data) and dried-up soil, the soil water pools can be depleted (reaching hygroscopic water content). In this case evaporation and transpiration fluxes are limited. This water content is calculated from pF=6.2 value based on he soil properties. Hygroscopic water content also becomes the lower limit for decomposition calculation.

Note that soil C and N pools are not distributed among the soil layers (only mineralized N is distributed within the layers). Decomposition of litter and soil organic matter is driven by average soil moisture and soil temperature of the entire root zone.

Poorly drained forests (e.g. in boreal regions or in lowland areas) are special ecosystems where groundwater and flooding play an important role in soil hydrology and plant growth (Pietsch et al., 2003; Bond-Lamberty et al., 2007). In order to enable groundwater (vertically varying soil water saturation) effect on the ecosystems in Biome-BGC MuSo v2.2 we implemented an option to supply external information about the depth of the water table.
Groundwater depth is controlled by prescribing the depth of saturated zone (groundwater) within the soil (note that the groundwater implementation of Pietsch et al. (2003) and Bond-Lamberty et al. (2007) is different from our approach). We assume that the user has information about groundwater depth from measurements or from another model (e.g. watershed hydrology model).
During the normal phase of the simulation the model can read daily groundwater information defined by a text file (groundwater.txt). The file is supposed to be present next to the model executable (during spin-up this option is not possible). If the file is not present, no groundwater manipulation is happening in normal phase.
The structure of groundwater.txt is simple (day of year, then groundwater depth in meters (negative value!) for the given day). Note that the current model version does NOT take into account the day of year field in the file. The User should check whether the length of the groundwater file is in accordance with the length of the normal simulation.
The model logic is the following: if (for a given day) groundwater depth is higher than the middle point of a given soil layer (e.g. if groundwater depth is -2.3 m while middle layer of the 5th layer is -2.5 m) then it is assumed that the entire layer (and all layers below that layer) is saturated. Upward diffusion of water from the saturated layes is possible according to the multilayer soil moisture implementation described above.
In the original Biome-BGC the effect of changing soil water content on photosynthesis and decompositon of soil organic matter is expressed in terms of soil water potential. Instead of the soil water potential, the volumetric soil moisture content is also widely used to calculate the limitation of stomatal conductance and decomposition. A practical advantage of soil moisture content as a stress function is that it is easy to measure in the field. The disadvantage is that soil moisture content is not comparable among different soil types. A possible solution to calculate a limiting factor from soil moisture content is to take into account the *relative soil moisture content* (or in other words, *relative soil water content;* RSWC), which is the ratio of the actual moisture content and the soil moisture content at field capacity (field capacity depends on soil texture) (Reichstein, 2001). In Biome-BGC MuSo v2.2 the scalar functions representing soil moisture limitation on photosynthesys and decomposition is expressed by RSWC (see below).

1.2.3 Modified decomposition and root respiration control

Within Biome-BGC, decomposition processes are influenced by soil temperature and soil water status. Instead of the averaged soil temperature and soil water status of the whole soil column, the average temperature and soil moisture content of the actual root zone is used by the decomposition calculation. The depth of the root zone is calculated based on above mentioned rooting depth.
The average temperature of each soil layer in the root zone is used to calculate the respiration of the fine and coarse roots.
As saturation of the soil causes anoxic conditions, groundwater can affect decomposition of soil organic matter (thus N mineralizaiton; Bond-Lamberty et al., 2007). As soil moisture control is implemented as effect of average (relative) soil moisture content within the entire root zone, the stress function affecting decomposition has been modified. Note that the new stress function is a linear function of relative soil water content, which is – due to the

definition of soil water potential – similiar to the original, non-linear function (the higher the relative soil moisture content is the lower the value of the stress function). The mininum reltive soil mositure content is related to hygroscopic water while the maximum is related to saturation. Note that close to saturation the decomposition becomes limited again. If mean (relative) soil moisture content is greater than a critical value (halfway between field capacity and saturation), a linear ramp function is implemented to limit decomposition to increase stress function. The shape of the modified stress function is similar to the one presented in Bond-Lambery et al. (2007; their Fig. 1).
In summary, Biome-BGC MuSo v2.2 uses the following scalar ($coeff_{decomp}$; with value between 0 and 1) to control decomposition in response to changing soil water content:

$$coeff_{decomp} = 0, \text{ if } RSWC_{act} \leq RSWC_{hw}$$

$$coeff_{decomp} = \frac{RSWC_{sat} - RSWC_{act}}{RSWC_{sat} - RSWC_{hw}}, \text{ if } RSWC_{hw} < RSWC_{act} < RSWC_{opt}$$

$$coeff_{decomp} = \frac{RSWC_{sat} - RSWC_{act}}{RSWC_{sat} - RSWC_{opt}}, \text{ if } RSWC_{opt} < RSWC_{act} < RSWC_{sat}$$

where $RSWC_{hw}$ is relative soil moisture (or soil water) content (RSWC) at hygroscopic soil water content, $RSWC_{act}$ is the actual RSWC, $RSWC_{wp}$ is RSWC at wilting point, and $RSWC_{sat}$ is RSWC at saturation. $RSWC_{opt}$ is RSWC halfway between field capacity and saturation.
The graphical representation of the soil moisture control is presented in Fig. 1.

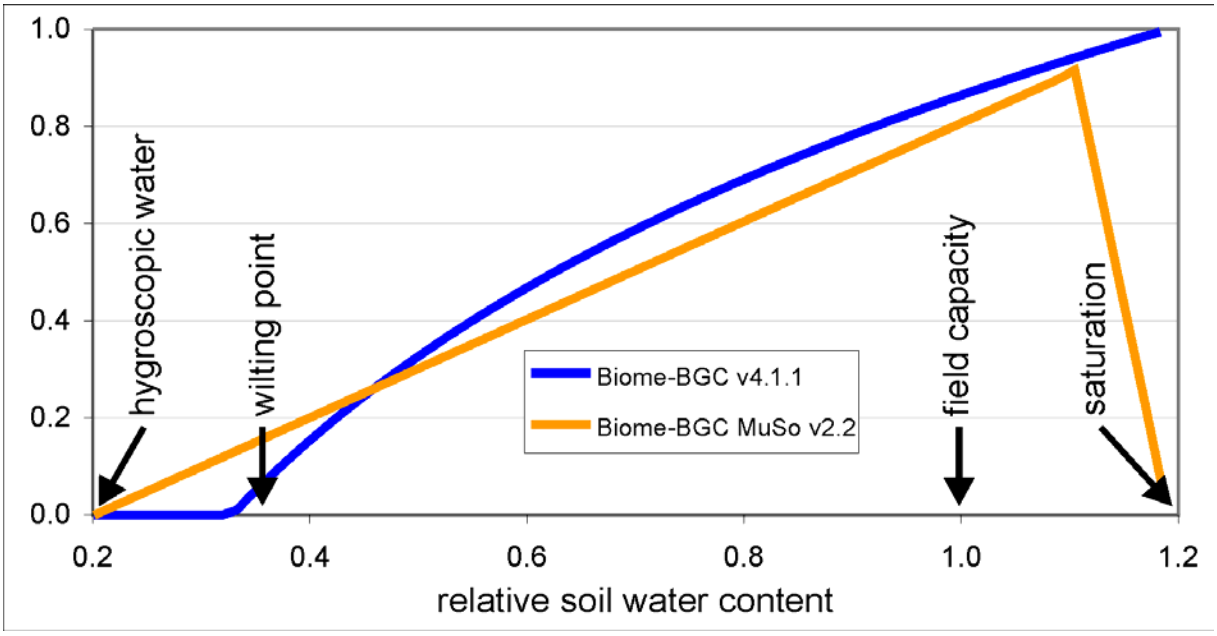

Figure 1. Scalar function of soil water content controlling decomposition in the original Biome-BGC v4.1.1, and in Biome-BGC MuSo v2.2.

1.2.4 Simulation of the soil mineral nitrogen content in multilayer soil

In the original model version uniform distribution of mineral nitrogen was assumed within the soil. In Biome-BGC MuSo v2.2 we assume that varying amount of mineralized nitrogen is available within the different soil layers that is available for root uptake (and other losses; its

actual value also depends on the actual rooting depth). We calculate the change in content of soil mineral nitrogen layer by layer, day by day. In the root zone the changes of mineralized N are caused by soil processes (decomposition, microbial immobilization and plant uptake), leaching, deposition and biological fixation. The produced/consumed N (calculated by decomposition and daily allocation functions) is distributed within the layers of root zone based on their soil mineral N content. Atmospheric N deposition goes to the first (0-10 cm) soil layer. Biological N fixation is divided between rootzone layers based on the quantity of the root in the given layer (calculated in multilayer_rootdepth.c). In the further soil layers (where no roots can be found) N content is changed only by leaching. Leaching is calculated based on the original empirical function of Biome-BGC.

1.3 Improvement of stomatal conductance calculation

In Biome-BGC the stomatal conductance calculation is based on environmental limiting factors. Stomatal conductance is calculated as the product of the maximum stomatal conductance and limiting stress functions based on minimum temperature, vapor pressure deficit and soil water potential. To calculate the limiting stress functions for each variable we set threshold limits within which the relative limiting effect was assumed to vary from fully constrained (0) to unconstrained (1). The values of the limits regarding to the different variables can be set by parameters.
Using the original Biome-BGC v4.1.1 (with the modifications described by Trusilova et al., 2009) we experienced unrealistic peaks in stomatal conductance, and consequently in the carbon and water fluxes. The reason for this phenomenon is that there are peaks in the stress function of soil water potential and therefore in stomatal conductance. Due to the functional form of soil water potential dependence on volumetric soil moisture content, the decrease of soil moisture content causes small increase in soil water potential at high soil moisture content. This means that close to the saturation (high soil moisture content) soil water potential is not sensitive to the decrease in the soil moisture content. Consequently, the stress function of soil water potential and therefore stomatal conductance is not decreasing significantly despite of the decrease in the soil moisture content. At lower soil moisture status a small decrease in soil moisture can cause huge decrease in soil water potential.
To avoid the occurrence of this phenomenon we have modified the model to use relative (actual values relative to field capacity) soil moisture content to define the stress function instead of soil water potential (note that the new stress function is a linear function of relative soil water content between specific points; see below). If enough soil water is available e.g. near field-capacity (no water stress) the stress function is equal to 1. If the conductance reduction is complete (serious water stress), the stress function is equal to zero. The start and the end of the water stress are determined using new ecophysiological parameters: soil water content ratio at the start of the conductance reduction and at the complete conductance reduction. The default soil water content threshold limit values are field capacity and wilting point, respectively.
Presence of elevated groundwater can negatively affect stomatal conductance (Bond-Lamberty et al., 2007). As soil moisture control is implemented as effect of average (relative) soil moisture content within the entire root zone, the stress function affecting stomatal conductance has been modified in MuSo v2.2. If mean (relative) soil moisture content is above a critical soil moisture content (halfway between field capacity and saturation) linear ramp function is implemented to limit stomatal conductance up to saturation (complete closure). The shape of the modified stress function is similar to the one presented in Bond-Lambery et al. (2007; their Fig. 1).

The model requires only one soil moisture stress function to calculate stomatal conductance, and soil water status is calculated layer by layer. Therefore, averaged stress function is necessary, which is the average of the layer factors weighted by the thickness of the layers of the root zone (where root can be found).
In summary, Biome-BGC MuSo v2.2 uses the following scalar ($coeff_{stoma}$; with value between 0 and 1) to control stomatal conductance in response to changing soil water content:

$$coeff_{stoma} = 0, \text{if } RSWC_{act} \leq RSWC_{wp}$$

$$coeff_{stoma} = \frac{RSWC_{fc} - RSWC_{act}}{RSWC_{fc} - RSWC_{wp}}, \text{if } RSWC_{wp} < RSWC_{act} < RSWC_{fc}$$

$$coeff_{stoma} = 1, \text{if } RSWC_{fc} < RSWC_{act} < RSWC_{opt}$$

$$coeff_{stoma} = \frac{RSWC_{sat} - RSWC_{act}}{RSWC_{sat} - RSWC_{opt}}, \text{if } RSWC_{opt} < RSWC_{act} < RSWC_{sat}$$

where $RSWC_{act}$ is the actual RSWC, $RSWC_{wp}$ is RSWC at wilting point, $RSWC_{fc}$ is RSWC at field capacity, and $RSWC_{sat}$ is RSWC at saturation. $RSWC_{opt}$ is RSWC halfway between field capacity and saturation.
The graphical representation of the soil moisture control is presented in Fig. 2.

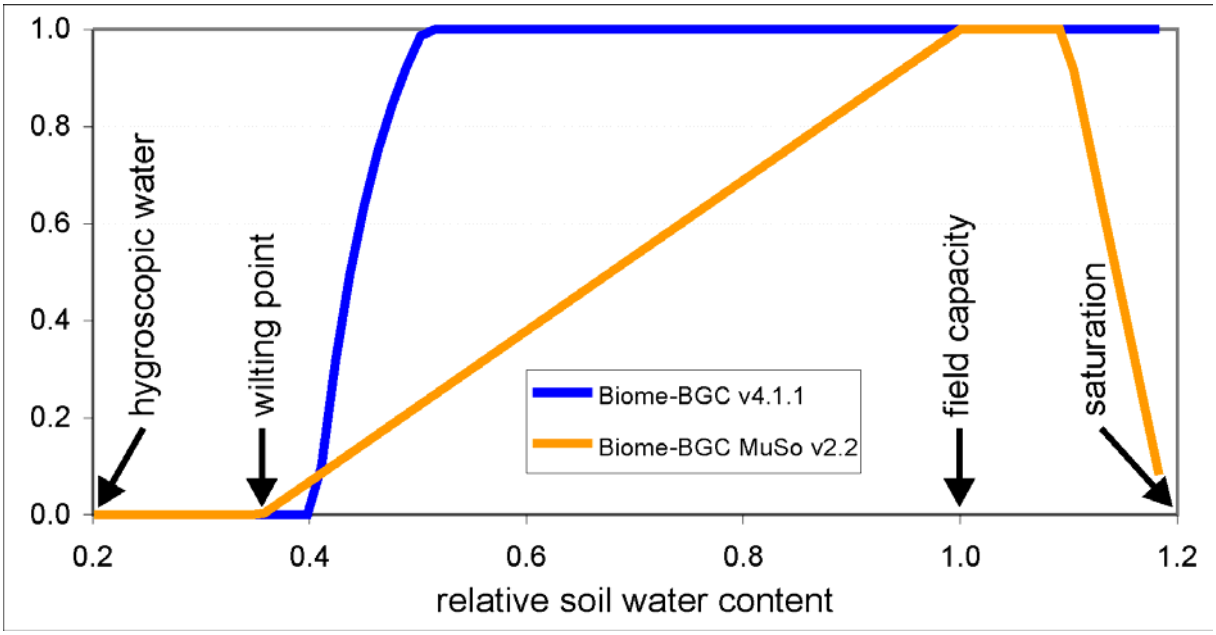

Figure 2. Scalar function of soil water content controlling stomatal conductance in the original Biome-BGC v4.1.1, and in Biome-BGC MuSo v2.2.

1.4 Modeling the effect of drought on the biogeochemical processes of the vegetation

As we mentioned, the stomatal conductance calculation is based on environmental limiting factors. The most important limiting factor is the soil water status: if the plant available water decreases due to the prolonged low level of precipitation (drought), the stomatal conductance, and so the carbon uptake will decrease. In the original model when the stress ends, the limitation of the stomatal conductance also ends and the simulated carbon uptake returns to the original value. It means that the original model ignores plant wilting and associated senescence (where the latter is an irreversible process) caused by soil drought.

In order to solve this problem a new module was implemented to simulate the ecophysiological effect of drought stress on plant mortality. If the plant available water decreases below a critical value, the new module starts to calculate the number of the days under drought stress. Soil water status is assumed to be critical if the averaged soil moisture content stress function of the rootzone is less than 0.1.
Due to low soil water content during a prolonged drought period (number of days since water stress is calculated in waterstress_days.c) abovegroung and belowground plant material senescence is occurring (actual, transfer and storage carbon and nitrogen pools) and the senescenced biomass is translocated into the litter pool. The senescence mortality coefficient of aboveground and belowground plant material can be set in EPC file (parameter 52-53). Mortality fluxes first enter a temporary sensecence pool (standing dead biomass) from which dead plant material gradually enters the litter pool. The turnover rate of dead plant material can be set in EPC file (parameter 54). The turnover rate is higher (multiplier is set to 1.5) in case of high precipitation (critical value: runoff value) or in case of grazing (due to trampling). This model feature was added to optionally simulate non-decomposing, intact dead plant material which can strongly modulate e.g. daily total ecosystem respiraiton in drought-prone semi-arid or arid ecosystems. Note that this feature is not expected to change the long term carbon balance of the ecosystem, but it might cause temporal redistribution of daily fluxes (delayed decomposition of senescenced leaves).

A2. Implementation of management modules

To simulate the effect of management activities on the carbon, nitrogen and water pools we defined new fluxes within the pools, and between the pools and the environment. The parameters of the new modules can be set by the user through the initialization files.
Since the release of MuSo v2.1 the model contains an important development: the User can define 7 different events for each management activitiy, and additionally annually varying management activities can be defined. The events can either be defined in the INI file (using this method the same events with the same timing will happen each year) or in an external control file (this case the management events can be defined separately for each year).

2.1 Mowing

Mowing can be simulated based on the one-sided LAI before and after mowing: due to mowing the carbon, nitrogen and water content (actual, transfer and storage pools as well) of the leaf and fruit decrease corresponding to the decrese of the LAI. We defined two possible ways of mowing calculation: based on before-mowing value (which means that mowing is occurred when the value of the LAI reaches a fixed value; fixLAI method); or based on selection of pre-defined days (regardless from the value of LAI; fixday_method).
Simulation of mowing is not possible out of the growing season because in the dormant period the content of leaf carbon and nitrogen pool is assumed to be zero in Biome-BGC for herbaceous ecosystems.
After mowing the cut-down fraction of the aboveground biomass can be taken away or can be left at the site. In the first case the cut-down plant material is excluded from the further calculations, the cut-down fraction of plant material (carbon and nitrogen) is a net loss for the system. In the second case cut-down plant material first goes into a temporary pool from which it gradually enters the litter pool. Althoug mowing is not possible outside of the growing season, this temporary pool can contain plant material also in the dormant period (depending on the amount of the cut-down material and the turnover rate of the cut-down non-

woody biomass). This logic was applied because observations indicated that respiration fluxes are unrealistic if we assume that harvested biomass turns immediately into litter pool The turnover rate (of mowed/harvested biomass to litter; TRMB) can be set in EPC file (parameter 55). The plant material returning into litter compartment is divided between the different types of litter pools according to EPC parameterization. The water stored in the canopy of the cut-down fraction is assumed to be evaporated.
Eight parameters are defined to simulate mowing (in the MOWING section of the INI file):

- flag for choosing the type of mowing simulation method (MOWING on predefined day or MOWING if LAI is greater than a predefined value)
- predefined value of the LAI before MOWING (in case of predefined value method)
- day of the year of mowing (in case of predefined day method)
- the value of *LAI* after mowing (determines MOWING effect)
- transported part of plant material

Note that the last three parameters have to be repeated seven times in the INI files of MuSo v2.2. If the user only want to use a subset of the maximum 7 events, 999.9 should be written to the unused places (see Appendix B for example). This is also true for the other management events described below.

2.2 Grazing

In case of grazing a given amount of leaf material is consumed by animals every day when grazing occurs. An important parameter used to simulate the effect of grazing is the livestock unit (*LSU*). *LSU* is a unit used to compare or aggregate different animal species and 1 *LSU* is equivalent to 500 kg live weight (1 adult cattle = 1 *LSU*).
In case of grazing the following parameters determine the decrease of the plant material:

- first and last day of grazing period
- animal stocking rate regarding a unit area
- daily ingested dry matter regarding a unit *LSU*
- proportion of ingested dry matter which turns into excrement
- proportion of excrement returning to litter
- carbon content of dry matter
- carbon and nitrogen content of manure.

Besides defoliation effect of grazing (i.e. intake by animals) it is also important that a fixed proportion of the above ground biomass flows to the litter compartment as the results of the excretal returns. The amount of dead plant material returning to litter is divided among the different type of litter pools according to their labile, cellulose and lignin ratios defined in the model.

2.3 Harvest

As management is not part of the original model logic, modifications are needed for cropland related application of Biome-BGC.
In agriculture, harvest is the process of gathering mature crops from the fields. It means that the effect of harvest is similar to effect of mowing but the fate of the cut-down fraction of aboveground biomass has to be defined. We assume that after harvest snags remain on the field as part of the living biomass, and part of the plant residue is also left on the field (in the form of litter). Yield is always transported away from the field, while stem and leaves can be transported away (and utilized e.g. as animal bedding) or can be left at the site. The ratio of harvested biomass that is taken away from the field has to be defined as a parameter. It is

expected that evolution of soil carbon pool will be highly dependent on the residue management practice, which is the result of human decision.
From the leaf area index of snag (model parameter), the effect of harvest on the carbon, nitrogen and water pools of living biomass can be calculated. The fluxes determining the decrease of the pools are calculated from the ratio of LAI before the harvest and the LAI of the snag. Similar to mowing, the harvested leaf biomass can be taken away or can be left at the site. In the first case the cut-down plant material is excluded from the further calculations, the cut-down fraction of plant material (carbon and nitrogen) is a net loss from the system. In the second case cut-down plant material first goes into a temporary pool from than gradually enters the litter pool. The turnover rate (of mowed/harvested biomass to litter; TRMB) can be set in EPC file (parameter 55). Althoug harvest is not possible outside of the growing season this temporary pool can contain plant material also in the dormant period (depending on the amount of the cut-down material and the turnover rate of the cut-down non-woody biomass). The plant material returning into litter compartment is divided between the different types of litter pool according to parameterization. The water stored in the canopy of the cut-down fraction is assumed to be evaporated.

2.4 Ploughing

Ploughing means farming for initial cultivation of soil in preparation for sowing seed or planting. The primary purpose of ploughing is to turn over the upper layer of soil bringing fresh nutrients to the surface, while allowing the remains of previous crops to break down and return to the soil. Since the soil model of Biome-BGC is multilayered the effect of layers turnover could be taken into account (e.g. uniform distribution of the soil mineral nitrogen content and/or soil water content in the layers affected by ploughing). We assume that due to the plough all the plant material of snag (remaining after harvest) returns the litter pools. The plant material returning into litter compartment is divided between the different types of litter pools. Parameter used to simulate ploughing is the day(s) of year of ploughing.

2.5 Fertilizing

Fertilization is necessary to supplement naturally occurring essential elements in the soil to maintain an optimum supply for plant growth. Fertilizers are chemical or organic compounds usually applied through the soil for uptake by plant roots. The most important effect of fertilization in Biome-BGC is the increase of soil nitrogen. Parameters used to simulate fertilization are:

- day of year of fertilizing
- quantity of fertilizer put out on a given fertilizing day
- nitrate, ammonium and carbon content of fertilizer
- labile, unshielded, shielded and cellulose fraction of fertilizer
- efficiency of utilization of fertilizer N by plants
- dissolving coefficient to define the amount of the nitrogen which returns to litter pool on a given day

We define an actual pool which contains the whole amount of fertilizer's nitrogen put out onto the ground on a given fertilizing day (actual pool of fertilizer; APF). On the fertilizing day the whole amount of fertilizer (QF) flows into APF. A fixed proportion (EC) of the fertilizer enters top soil layer on a given day after fertilizing. Not all this fraction gets into the soil pools because a given proportion is leached; this is determined by the efficiency of utilization. Nitrate content of fertilizer can be taken up by plant directly, therefore we assume that it goes into the soil mineral pool. Ammonium content of fertilizer has to be nitrified

before taken up by plant, therefore turn into the litter nitrogen pool. Carbon content of fertilizer turns into the litter carbon pool. Therefore APF decreases day-to-day after fertilizing until becomes empty, which means that the effect of the fertilization ends.

2.6 Planting

Planting is the process of introducing seeds into the soil (sowing). In Biome-BGC transfer pools are defined to contain plant material as germ in the dormant season from which carbon and nitrogen gets to the normal pools (leaf, fruit, root) in the beginning of the growing season. In order to simulate the effect of sowing we assume that the plant material which is in the planted seed goes into the transfer pools thus increasing its content. Allocation of leaf, fruit and root from seed is calculated based on allocation parameters in EPC file (parameter 13-14). We assume that a given part of the seed is destroyed before sprouting. Parameters used to simulate planting are:

- day of year of planting
- quantity of seed on a given planting day
- the carbon content of seed
- the useful part of seed (not destroyed before sprouting)

The nitrogen content of leaf, fruit and root can be calculated using ecophysiological parameters: carbon and nitrogen ratio of leaf, fruit and root (EPC parameters 19-22).

2.7 Thinning

In forestry thinning is the selective removal of trees, primarily undertaken to improve the growth rate or health of the remaining trees, and to create profit (through wood products).
We assume that based on a thinning rate (the proportion of the removed trees) the decrease of leaf, stem and root pools can be determined. After thinning the cut-down fraction of the aboveground biomass can be taken away or can be left at the site. The rate of transported stem and/or leaf can be set by the user. The transported plant material is excluded from the further calculations. The plant material translocated into CWD or litter compartments are divided between the different types of litter pools according to parameterization (coarse root and stem goes into the CWD pool; if harvested stem is taken away from the site only coarse root goes to CWD; note that storage and transfer pools of woody harvested material are translocated into the litter pool).
Parameters used to simulate thinning are:

- day of year of thinning
- thinning rate
- transported part of stem
- transported part of leaf

The handling of the cut down non-removed pools is different for stem, roots and leaves. Stem (live and deadwood; see Thornton (2000) for definition of deadwood in case of Biome-BGC!) is immediately translocated into cwd without any delay. However, for stump and leaves implementation of an intermediate turnover process was neccessary to avoid C and N balance errors caused by sudden changes between specific pools. The parameter „Turnover rate of cut-down non-removed non-woody biomass to litter" (TRCN; controlled within the EPC file) controls the fate of (previously living) leaves on cut down trees, and it also controls the turnover of dead coarse root (stump) into coarse woody debris (cwd).

A3. Other modifications

3.1 Implementation of annually varying whole plant mortality (dynamic mortality)

Annual whole-plant mortality fraction (WPM) is part of the ecophysiological parameterization of Biome-BGC (user supplied value), which means that it is assumed to be constant throughout the simulation. From the point of view of forest growth constant mortality can be considered as a rough assumption. Ecological knowledge suggest that WPM varies dynamically within the lifecycle of forest stands due to competition for resources or due to competition within tree species (plus many other causes).
In order to enable more realistic forest stand development we implemented an option for supplying annually varying WPM to Biome-BGC MuSo. During the normal phase of the simulation the model can either use constant mortality, or it can read annually varying WPM defined by a text file (mortality.txt) which is supposed to be present next to the model executable (during spin-up only constant mortality is possible). The structure of mortality.txt is the same as the structure of the annually varying CO_2 concentration file or the annually varying N deposition file (year, then WPM for a given year). Note that the current model version does NOT take into account the year field in the mortality.txt file (this is true for the CO_2 and N deposition file): for the first year of the simulation the first line is used (regardless of the value of the year field); for the second year the second line is used etc.

3.2 Correction of bug related to the calculation of daylight average temperature

According to the Biome-BGC User's Guide 4.2 there was a bug in the source code of the model that is related to the calculation of daylight average temperature (Thornton and Running, 2002): *„An incorrect parameter was being used in the calculation of the daylight average air temperature in daymet.c. The parameter value in version 4.1.1 was 0.212, and the correct value, for consistency with the MT-CLIM and Daymet code, should be 0.45. The daylight average air temperature (tday) is used in the photosynthesis routine, and in the calculation of daytime leaf maintenance respiration. As an example of the net result of changing to the correct value, the example simulations described later in this guide show an increase in steady state leaf area index of about 10% and an increase in steady state net primary production of about 5%. Thanks to Michael Guzy at Oregon State University for finding this bug."*
We corrected this bug but not in terms of the parameter in daymet.c, but we modified the model in order to use the daylight average temperature value that is provided by the meteorological input file (MTClim output in many cases). We prefer this solution as the user of the model can use his/her own calculation method for daylight average temperature (e.g. based on hourly measurements), which would be meaningless if the model would re-calculate its value based on daily maximum and minimum temperature.

3.3 Fruit simulation

In order to enable carbon and nitrogen budget simulation of croplands with Biome-BGC MuSo, fruit (or grain) simulation was implemented. After the flowering date (defined in EPC file; parameter 6) fruit starts to grow; therefore growth and maintenence respiration, daily allocation, mortality, phenology and litterfall routines are completed with fruit simulation. Besides flowering date there are 5 additional new EPC parameters: new fruit carbon ratio to new leaf carbon, carbon and nitrogen ratio of fruit and labile, cellulose and lignin proportion of fruit. Note that fruit simulation can be completely switched off with setting the „new fruit carbon ratio to new leaf carbon" allocation parameter to zero (parameter 16).

3.4 New C4 photosynthesi routine

Based on the work of Di Vittorio et al. (2010) we implemented a new, enzyme-driven C4 photosynthesis routine into he photsynthesis module. In case of C3 photosynthesis pathway the EPC parameter „fraction of leaf N in PEP Carboxylase" parameter has no effect on the simulation. However, the EPC parameter „fraction of leaf N in Rubisco" also affects the process of photosynthesis in case of both pathways (see Di Vittorio et al., 2010 for details).

APPENDIX B
EXAMPLE INI FILE FOR BIOME-BGC MUSO V2.2

```
BBGC_MuSo simulation

MET_INPUT
metdata/bugac_1901_2000.mtc43        (filename) met file name
4                                    (int) number of header lines in met file

RESTART
0                        (flag) 1 = read restart; 0 = dont read restart
1                        (flag) 1 = write restart; 0 = dont write restart
0                        (flag) 1 = use restart metyear; 0 = reset metyear
restart/bugac _MuSo13.endpoint          (filename) name of the input restart file
restart/bugac _MuSo13.endpoint          (filename) name of the output restart file

TIME_DEFINE
100                              (int) number of meteorological data years
100                              (int) number of simulation years
1901                             (int) first simulation year
1                                (flag) 1 = spinup run; 0 = normal run
6000                             (int) maximum number of spinup years

CLIM_CHANGE
0.0                           (degC) - offset for Tmax
0.0                           (degC) - offset for Tmin
1.0                           (degC) - multiplier for PRCP
1.0                           (degC) - multiplier for VPD
1.0                           (degC) - multiplier for RAD

CO2_CONTROL
1                             (flag) 0=constan; 1=vary with file; 2=based on Ndep
385.8                         (ppm) constant atmospheric CO2 concentration
co2/CO2_1901-2011.txt         (filename) name of the CO2 file

SITE
1.00                         (m) maximum depth of rooting zone
85.3                         (%) sand percentage by volume in rock-free soil
5.9                          (%) silt percentage by volume in rock-free soil
8.8                          (%) clay percentage by volume in rock-free soil
111.4                        (m)  site elevation
46.69                        (degrees) site latitude (- for S.Hem.)
0.20                         (DIM) site shortwave albedo
0.00020                      (kgN/m2/yr) wet+dry atmospheric deposition of N
0.00050                      (kgN/m2/yr) symbiotic+asymbiotic fixation of N
11.00                        (Celsius) mean annual air temperature
0.1                          runoff parameter (Campbell, 1988)
0.51                         (m3/m3) measured SWC at SAT (if no data: 999.9)
0.25                         (m3/m3) measured SWC at FC (if no data: 999.9)
0.05                         (m3/m3) measured SWC at WP (if no data: 999.9)

RAMP_NDEP
0                      (flag) do a ramped N-deposition run? 0=no, 1=yes
2050                   (int)  reference year for industrial N deposition
0.00200                              (kgN/m2/yr) industrial N deposition value
nitrogen/Ndep_1901-2011.txt          (filename)  name of the N-dep file

EPC_FILE
epc/apriori_MuSo13_c3grass.epc       (filename) EPC file name

W_STATE
0.0                        (kg/m2)   water stored in snowpack
0.5                        (DIM)     initial soil water as a proportion of saturation

C_STATE
0.001                      (kgC/m2)  first-year maximum leaf carbon
0.0                        (kgC/m2)  first-year maximum stem carbon
0.0                        (kgC/m2)  coarse woody debris carbon
0.0                        (kgC/m2)  litter carbon, labile pool
0.0                        (kgC/m2)  litter carbon, unshielded cellulose pool
0.0                        (kgC/m2)  litter carbon, shielded cellulose pool
0.0                        (kgC/m2)  litter carbon, lignin pool
0.0                        (kgC/m2)  soil carbon, fast microbial recycling pool
0.0                        (kgC/m2)  soil carbon, medium microbial recycling pool
0.0                        (kgC/m2)  soil carbon, slow microbial recycling pool
```

```
0.0                     (kgC/m2)  soil carbon, recalcitrant SOM (slowest)

N_STATE
0.0                     (kgN/m2)  litter nitrogen, labile pool
0.0                     (kgN/m2)  soil nitrogen, mineral pool

GROWING_SEASON
5.0                    (kgH2O/m2) critical amount of snow limiting photosyn (no data: 999.9)
1                      (flag) use GSI index to calculate growing season
5.00                   (Celsius) basic_temperature to calculate heatsum
1.00                   (Celsius) limit1 (under:full constrained) of HEATSUM index
10.00                  (Celsius) limit2 (above:unconstrained) of HEATSUM index
-2.00                  (Celsius) limit1 (under:full constrained) of TMIN index
5.00                   (Celsius) limit2 (above:unconstrained) of TMIN index
4000                   (Pa) limit1 (above:full constrained) of VPD index
1000                   (Pa) limit2 (under:unconstrained) of VPD index
0                      (s) limit1 (under:full constrained) of DAYLENGTH index
0                      (s) limit2 (above:unconstrained) of DAYLENGTH index
10                     (day) moving average (to avoid the effects of extreme events)
0.10                   GSI limit1 (greater that limit -> start of vegper)
0.01                   GSI limit2 (less that limit -> end of vegper)
intvar/GSI_bugac_2003-2011.txt         file of the estimated start and end of the VP

OUTPUT_CONTROL
outputs/bugac_2003-2011_ MuSo
intvar/ctrl.txt    file of the BBGC variables (control)
1                  (flag)  1 = write daily output   0 = no daily output
0                  (flag)  1 = monthly avg of daily variables  0 = no monthly avg
0                  (flag)  1 = annual avg of daily variables   0 = no annual avg
0                  (flag)  1 = write annual output  0 = no annual output
1                  (flag)  for on-screen progress indicator

DAILY_OUTPUT
5        number of daily output variables
623                 GPP
649                  TR
34                  LHF
509                 LAI
638               soilC

ANNUAL_OUTPUT
10       number of annual output variables
545     ann max projLAI
628              cumNPP
630              cumNEE
631              cumGPP
632               cumMR
633               cumGR
634               cumHR
636                vegC
638               soilC
639              totalC

--------------------
MANAGEMENT_SECTION
--------------------
PLANTING
0                    (flag) do PLANTING? 0=no; 1=yes; filepath=reading from file'
10 999.9 999.9 999.9 999.9 999.9 999.9                  (yday)  PLANTING day
10.0  10.0  10.0  10.0  10.0  10.0  10.0    (double) quantity of seed (kg seed/ha)
40   40   40   40   40   40   40            (%)  C content of seed
90   90   50   50   50   50   50            (%) useful part of seed

THINNING
0                    (flag) do THINNING? 0=no; 1=yes; filepath=reading from file'
150 999.9 999.9 999.9 999.9 999.9 999.9            (yday)  THINNING day
0.5 0.5 0.5 0.5 0.5 0.5 0.5            (prop) thinning rate
100 100 100 100 100 100 100            (%) transported part of stem
100 100 100 100 100 100 100            (%) transported part of leaf

MOWING
0                  (flag) do MOWING? 0=no; 1=yes; filepath=reading from file
0                  (flag) mowing method? 0 - on fixday method, 1 - fixLAI method
6.0                               (int) fixed value of the LAI before MOWING (fixLAI method)
1.0                               (int) fixed value of the LAI after MOWING (fixLAI method)
150 234 999.9 999.9 999.9 999.9 999.9       (yday) MOWING day (fixday method)
1.0 1.0 1.0 1.0 1.0 1.0 1.0       (int) value of the LAI after MOWING (fixday method)
```

```
0   0   0   0   0   0   0         (%) transported part of plant material

GRAZING
0                     (flag)                do GRAZING? 0=no, 1=yes; filepath=reading from file
120 200 999.9 999.9 999.9 999.9 999.9                (yday) first day of GRAZING
200 280 999.9 999.9 999.9 999.9 999.9                (yday) last day of GRAZING
15.0  15.0  15.0  15.0  15.0  15.0  15.0        (kg dry matter/LSU) daily ingested dry matter
0.75  0.75  0.75  0.75  0.75  0.75  0.75    (LSU/ha) animal stocking rate: Livestock Units ha
25  25  25  25  25  25  25                   (%) prop. proportion of DM intake formed excrement
100 100 100 100 100 100 100                  (%)     prop. excrement returning to litter
40  40  40  40  40  40  40                   (%)     carbon content of dry matter
5   5   5   5   5   5   5                    (%)    N content of manure
40  40  40  40  40  40  40                   (%)    C content of manure

HARVESTING
0                                (flag) do HARVESTING? 0=no, 1=yes; filepath=reading from file
200 999.9 999.9 999.9 999.9 999.9 999.9      (yday) HARVESTING day
1.0 1.0 1.0 1.0 1.0 1.0 1.0      (m2/m2) LAI after HARVESTING (snag)
100 100 100 100 100 100 100      (%) transported part of plant material

PLOUGHING
0                                 (flag) do PLOUGHING? 0=no, 1=yes; filepath=reading from file
200 999.9 999.9 999.9 999.9 999.9 999.9       (yday) PLOUGHING day

FERTILIZING
0                              (flag) do FERTILIZING? 0=no, 1=yes; filepath=reading from file
60 120 200 999.9 999.9 999.9 999.9              (yday) FERTILIZING day
30.0 30.0 30.0 30.0 30.0 30.0 30.0       (kgN/ha/day)(nitrogen from fertilization per day)
17  17  17  17  17  17  17               (%) nitrate content of fertilizer
17  17  17  17  17  17  17               (%) ammonium content of fertilizer
5   5   5   5   5   5   5                (%) carbon content of fertilizer
70  70  70  70  70  70  70               (%) labile fraction of fertilizer
20  20  20  20  20  20  20               (%) unshielded cellulose fraction of fertilizer
 0   0   0   0   0   0   0               (%) shielded cellulose fraction of fertilizer
10  10  10  10  10  10  10               (%) lignin  fraction of fertilizer
5   5   5   5   5   5   5                (%) dissolving coefficient
90  90  90  90  90  90  90               (%) useful part

END_INIT
```

APPENDIX C
EXAMPLE EPC FILE FOR BIOME-BGC MUSO V2.2

```
ECOPHYS       C3 grass
0     (flag) 1 = WOODY 0 = NON-WOODY
0     (flag) 1 = EVERGREEN 0 = DECIDUOUS
1     (flag) 1 = C3 PSN 0 = C4 PSN
1     (flag) 1 = MODEL PHENOLOGY 0 = USER-SPECIFIED PHENOLOGY
60    (yday) yearday to start new growth (when phenology flag = 0)
300   (yday) yearday to end litterfall (when phenology flag = 0)
150   (yday) yearday to flowering (start of fruit allocation)
1.0   (prop.)transfer growth period as fraction of growing season
1.0   (prop.)litterfall as fraction of growing season
1.0   (1/yr) annual leaf and fine root turnover fraction
0.00  (1/yr) annual live wood turnover fraction
0.05  (1/yr) annual whole-plant mortality fraction
0.0   (1/yr) annual fire mortality fraction
1.0   (ratio)(ALLOCATION) new fine root C : new leaf C
0.1   (ratio) (ALLOCATION) new fruit c : leaf c
0.00  (ratio)(ALLOCATION) new stem C : new leaf C
0.00  (ratio)(ALLOCATION) new live wood C : new total wood C
0.00  (ratio)(ALLOCATION) new croot C : new stem C
0.5   (prop.)(ALLOCATION) current growth proportion
25.0  (kgC/kgN)     C:N of leaves
45.0  (kgC/kgN)     C:N of leaf litter, after retranslocation
50.0  (kgC/kgN)     C:N of fine roots
25.0  (kgC/kgN)     C:N of fruit
0.00  (kgC/kgN)     C:N of live wood
0.00  (kgC/kgN)     C:N of dead wood
0.68  (DIM)  leaf litter labile proportion
0.23  (DIM)  leaf litter cellulose proportion
0.09  (DIM)  leaf litter lignin proportion
0.34  (DIM)  fine root labile proportion
0.44  (DIM)  fine root cellulose proportion
0.22  (DIM)  fine root lignin proportion
0.68  (DIM)  fruit litter labile proportion
0.23  (DIM)  fruit litter cellulose proportion
0.09  (DIM)  fruit litter lignin proportion
0.00  (DIM)  dead wood cellulose proportion
1.00  (DIM)  dead wood lignin proportion
0.01  (1/LAI/d) canopy water interception coefficient
0.5   (DIM)  canopy light extinction coefficient
2.0   (DIM)  all-sided to projected leaf area ratio
49.0  (m2/kgC) canopy average specific leaf area (projected area basis)
2.0   (DIM)  ratio of shaded SLA:sunlit SLA
0.2   (DIM)  fraction of leaf N in Rubisco
0.03  (DIM)  fraction of leaf N in PEP Carboxylase
0.006 (m/s)  maximum stomatal conductance (projected area basis)
0.00006 (m/s)cuticular conductance (projected area basis)
0.04  (m/s)  boundary layer conductance (projected area basis)
999.9 (m3/m3) soil water content ratio: start of cond. red. (999.9: field cap.)
999.9 (m3/m3) soil water content ratio: complete cond. red. (999.9: wilting point)
999.9 (MPa)  leaf water potential: complete cond.  reduction (999.9: SWCR is used)
999.9 (MPa)  leaf water potential: complete cond. reduction (999.9: SWCR is used)
1000  (Pa)   vapor pressure deficit: start of conductance reduction
5000  (Pa)   vapor pressure deficit: complete conductance reduction
0.01  (prop.) senescence mortality coefficient of aboveground plant material
0.01  (prop.) senescence mortality coefficient of belowground plant material
0.01  (prop.) turnover rate of wilted standing biomass to litter
0.05  (prop.) turnover rate of cut-down non-woody biomass to litter
0.001 (prop.) turnover rate of cut-down woody  biomass to litter
0.3   (prop.) growth resp per unit of C grown
0.01  (prop.) N denitrification proportion
0.1   (prop.) N mobilen proportion
0.5   (prop.)maturity coefficient
```

APPENDIX D
CHANGES IN THE OUTPUT VARIABLES AND THEIR CODE IN BIOME-BGC MUSO V2.2

Due to code modifications there are many changes in the output variables. Please see output_map_init.c for current list of variables. Note that in MuSo v2.2 total ecosystem respiration can be retrieved as a single output variable (`output_map[649]`) to support Monte Carlo experiments with large number of simulations (in order to save disk space).

New output variables (incomplete list; see above)

```
output_map[23] = &ws->soilw_SUM;

output_map[27] = &ws->soilevap_snk;
output_map[28] = &ws->snowsubl_snk;
output_map[29] = &ws->canopyevap_snk;
output_map[30] = &ws->trans_snk;
output_map[31] = &ws->runoff_snk;
output_map[32] = &ws->deeppercolation_snk;
output_map[33] = &ws->deepdiffusion_snk;
output_map[34] = &wf->evapotransp;

output_map[43] = &wf->soilw_trans_SUM;
output_map[44] = &wf->prcp_to_runoff;
output_map[45] = &wf->canopyw_to_THN;
output_map[46] = &wf->canopyw_to_MOW;
output_map[47] = &wf->canopyw_to_GRZ;
output_map[48] = &wf->canopyw_to_HRV;
output_map[49] = &wf->canopyw_to_PLG;

output_map[100] = &cs->fruitc;
output_map[101] = &cs->fruitc_storage;
output_map[102] = &cs->fruitc_transfer;

output_map[104] = &cs->THNsnk;
output_map[105] = &cs->THNsrc;
output_map[106] = &cs->MOWsnk;
output_map[107] = &cs->MOWsrc;
output_map[108] = &cs->GRZsnk;
output_map[109] = &cs->GRZsrc;
output_map[110] = &cs->HRVsnk;
output_map[111] = &cs->HRVsrc;
output_map[112] = &cs->PLGsnk;
output_map[113] = &cs->PLGsrc;
output_map[114] = &cs->PLTsrc;
output_map[115] = &cs->FRZsrc;
output_map[116] = &cs->SNSCsnk;
output_map[117] = &cs->SNSCsrc;

output_map[307] = &ns->sminn_RZ;

output_map[315] = &ns->THNsnk;
output_map[316] = &ns->MOWsnk;
output_map[317] = &ns->GRZsnk;
output_map[318] = &ns->GRZsrc;
output_map[319] = &ns->HRVsnk;
output_map[320] = &ns->HRVsrc;
output_map[321] = &ns->PLGsnk;
output_map[322] = &ns->PLGsrc;
output_map[323] = &ns->PLTsrc;
output_map[324] = &ns->FRZsrc;
output_map[325] = &ns->SNSCsnk;
output_map[326] = &ns->SNSCsrc;
```

```
output_map[546] = &epv->vwc[0];
output_map[547] = &epv->vwc[1];
output_map[548] = &epv->vwc[2];
output_map[549] = &epv->vwc[3];
output_map[550] = &epv->vwc[4];
output_map[551] = &epv->vwc[5];

output_map[621] = &summary->daily_nbp;

output_map[641] = &summary->Cchange_MOW;
output_map[642] = &summary->Cchange_HRV;
output_map[643] = &summary->Cchange_PLG;
output_map[644] = &summary->Cchange_GRZ;
output_map[645] = &summary->Cchange_FRZ;
output_map[646] = &summary->Cchange_PLT;
output_map[647] = &summary->Cchange_SNSC;
output_map[648] = &summary->daily_sr;
output_map[649] = &summary->daily_tr;
```

APPENDIX E
EXAMPLES FOR ANCILLARY MANAGEMENT FILES

Examples are given here for the content of the externally defined ancillary management types that is a new feature of Biome-BGC MuSo v2.2. Note that these examples assume that the simulation is performed for 3 years (i.e. the 7-event-lines are repeated 3 times). In any case, the 7-event lines have to be defined separately for each simulation years in each block. An example for ancillary file to describe mowing is already presented above so it is not given here. As the examples show,

Ancillary file for anually varying planting

```
PLANTING day
70  999.9 999.9 999.9 999.9 999.9 999.9
80  999.9 999.9 999.9 999.9 999.9 999.9
90  999.9 999.9 999.9 999.9 999.9 999.9
quantity of seed (kg seed/ha)
10 100 100 100 100 100 100
20 100 100 100 100 100 100
10 100 100 100 100 100 100
C content of seed
40  40  40  40  40  40  40
40  40  40  40  40  40  40
40  40  40  40  40  40  40
proportion of material of seed which produces leaf
50  50  50  50  50  50  50
50  50  50  50  50  50  50
50  50  50  50  50  50  50
```

Ancillary file for anually varying thining

```
THINNING day
150 999.9 999.9 999.9 999.9 999.9 999.9
150 999.9 999.9 999.9 999.9 999.9 999.9
150 999.9 999.9 999.9 999.9 999.9 999.9
THINNING rate
0.5 0.5 0.5 0.5 0.5 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5
rate of transported stem
0.5 0.5 0.5 0.5 0.5 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5
rate of transported leaf
0.5 0.5 0.5 0.5 0.5 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5
```

Ancillary file for anually varying grazing

```
FIRST DAY OF GRAZING
120  200  999.9  999.9  999.9  999.9  999.9
130  210  999.9  999.9  999.9  999.9  999.9
140  220  999.9  999.9  999.9  999.9  999.9
LAST DAY OF GRAZING
180  280  999.9  999.9  999.9  999.9  999.9
```

```
190  290  999.9  999.9  999.9  999.9  999.9
200  300  999.9  999.9  999.9  999.9  999.9
DAILY INGESTED DRY MATTER
15.0 16.0 15.0 15.0 15.0 15.0 15.0
15.0 15.0 15.0 15.0 15.0 15.0 15.0
15.0 15.0 15.0 15.0 15.0 15.0 15.0
ANIMAL STOCKING RATE
0.75 0.75 0.75 0.75 0.75 0.75 0.75
0.75 0.75 0.75 0.75 0.75 0.75 0.75
0.75 0.75 0.75 0.75 0.75 0.75 0.75
PROP. DM INTAKE FORMED EXCREMENT
25  25  25  25  25  25  25.0
25  25  25  25  25  25  25.0
25  25  25  25  25  25  25.0
PROP. EXCREMENT RETURNING TO LITTER
100  100  100  100  100  100  100
100  100  100  100  100  100  100
100  100  100  100  100  100  100
C CONTENT OF DRY MATTER
40   40   40   40   40   40   40
40   40   40   40   40   40   40
40   40   40   40   40   40   40
N CONTENT OF MANURE
5    5    5    5    5    5    5
5    5    5    5    5    5    5
5    5    5    5    5    5    5
C CONTENT OF MANURE
40   40   40   40   40   40   40
40   40   40   40   40   40   40
40   40   40   40   40   40   40
```

Ancillary file for anually varying harvesting

```
HARVESTING DAY
100 999.9 999.9 999.9 999.9 999.9
150 999.9 999.9 999.9 999.9 999.9 999.9
200 999.9 999.9 999.9 999.9 999.9 999.9
LAI AFTER HARVESTING (SNAG)
1.0 1.0 1.0 1.0 1.0 1.0 1.0
0.5 1.0 1.0 1.0 1.0 1.0 1.0
0.1 1.0 1.0 1.0 1.0 1.0 1.0
TRANSPORTED PART OF PLANT MATERIAL
100 100 100 100 100 100 100
100 100 100 100 100 100 100
100 100 100 100 100 100 100
```

Ancillary file for anually varying ploughing

```
PLOUGHING DAY
220 999.9 999.9 999.9 999.9 999.9 999.9 999.9
220 999.9 999.9 999.9 999.9 999.9 999.9 999.9
220 999.9 999.9 999.9 999.9 999.9 999.9 999.9
```

Ancillary file for anually varying fertilization

```
FERTILIZING DAY
60   120  220  999.9  999.9  999.9  999.9
60   120  220  999.9  999.9  999.9  999.9
60   120  220  999.9  999.9  999.9  999.9
```

```
NITROGEN FROM FERTILIZATION PER DAY
60.0 30.0 30.0 30.0 30.0 30.0 30.0
70.0 30.0 30.0 30.0 30.0 30.0 30.0
80.0 30.0 30.0 30.0 30.0 30.0 30.0
NITRATE CONTENT OF FERTILIZER
17.0 17.0 17.0 17.0 17.0 17.0 17.0
17.0 17.0 17.0 17.0 17.0 17.0 17.0
17.0 17.0 17.0 17.0 17.0 17.0 17.0
AMMONIUM CONTENT OF FERTILIZER
17.0 17.0 17.0 17.0 17.0 17.0 17.0
17.0 17.0 17.0 17.0 17.0 17.0 17.0
17.0 17.0 17.0 17.0 17.0 17.0 17.0
CARBON CONTENT OF FERTILIZER
5    5    5    5    5    5    5
5    5    5    5    5    5    5
5    5    5    5    5    5    5
LABILE FRACTION OF FERTILIZER
70   70   70   70   70   70   70
70   70   70   70   70   70   70
70   70   70   70   70   70   70
UNSHIELDED CELLULOSE FRACTION OF FERTILIZER
20   20   20   20   20   20   20
20   20   20   20   20   20   20
20   20   20   20   20   20   20
 SHIELDED CELLULOSE FRACTION OF FERTILIZER
0    0    0    0    0    0    0
0    0    0    0    0    0    0
0    0    0    0    0    0    0
LIGNIN  FRACTION OF FERTILIZER
10   10   10   10   10   10   10
10   10   10   10   10   10   10
10   10   10   10   10   10   10
DISSOLVING COEFFICIENT
8    8    8    8    8    8    8
8    8    8    8    8    8    8
8    8    8    8    8    8    8
USEFUL PART
90   90   90   90   90   90   90
90   90   90   90   90   90   90
90   90   90   90   90   90   90
```

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